Parcel-level model of water and energy end use: Effects of indoor water conservation

MIGUEL A. MORALES,[1] JAMES P. HEANEY,[1] KENNETH R. FRIEDMAN,[1] AND JACQUELINE M. MARTIN[2]

[1]Department of Environmental Engineering Sciences, University of Florida, Gainesville, Fla.
[2]E Sciences, Orlando, Fla.

This article presents a parcel-level methodology to estimate the water and energy savings associated with indoor water conservation best management practices (BMPs). By estimating fixture water savings at the parcel level for 64 public-supply land use sectors, this approach facilitates targeting customers for water conservation by calculating their net benefits for each end use (savings in charges for water, wastewater, and energy, minus cost of water conservation BMPs). The inclusion of energy savings, primarily through reduced hot water use, is shown to be a significant benefit. The modeled end uses are male-only toilets, mixed-use toilets, urinals, faucets, showerheads, clothes washers, and prerinse spray valves. This article concludes with a simplified optimization formulation that determines the best fixture choice for every end-use device so that net benefits at the parcel level are maximized. These individual fixture results are then aggregated to the parcel or any desired aggregate scale (e.g., utility).

Keywords: *water–energy nexus, end-use modeling, optimization, residential, commercial, conservation*

The intrinsic link between water and energy is well documented (USDOE, 2006). Water is required to produce electricity and energy is used to intake, treat, distribute, and use water, and to collect, treat, and dispose of wastewater or reuse treated wastewater. The California Energy Commission (2005) disaggregated energy use associated with urban water systems into water conveyance, treatment, and supply (20%), end use (75%), and wastewater collection and treatment (5%). Most of the energy use associated with the urban water cycle is direct use by the customer, largely in heating water for end uses such as showering and washing clothes. The percentage of energy use attributable to end uses is likely greater in other states such as Florida, where the energy use associated with water conveyance from source to water treatment is significantly lower than in California. A recent report for the Water Research Foundation (Leiby & Burke, 2011) includes water-demand management as a best practice, recognizing that reduced demands may result in reduced treatment and distribution needs, saving energy inputs. The predominance of the energy associated with water end uses serves as the impetus for this work, which is to present a parcel-level model of the water and energy savings associated with water conservation practices.

Existing water use models evaluate water savings at the aggregate level. Jacobs and Haarhoff (2004) devised a residential end-use model that addressed not only demand for potable water but also hot water, wastewater flow, and concentration of total dissolved solids in wastewater. This approach requires significant data inputs, relies on average values for a given service area to determine end uses, and does not allow for targeting of individual users or clusters of users most suitable for water conservation. The Least Cost Planning Demand Decision Support System model, a proprietary end-use model, has similar limitations in its lack of fine spatial data on water users and limited ability to target customers for water conservation (Maddaus & Maddaus, 2004).

Several models have been proposed to address the variability in indoor water use and demand-management options using probabilistic techniques. Rosenberg (2007) uses probability theory to derive a normalized performance function for evaluating conservation options. Blokker et al (2010, 2011) generate probabilistic demand estimates through simulation of end-use parameter probability distributions of various end-use parameters but do not explicitly use this model to develop optimal demand-management strategies. Other models estimate only energy use. Aydinalp et al (2004) modeled hot-water energy use in the residential sector using neural networks, but the effect of water conservation was not investigated. The same limitation exists in the work of Widen et al (2009), which modeled hourly electricity use through simple conversion schemes, mean appliance and water-tap data, and general daylight availability distributions.

Clark and Males (1985, 1986) presented the Water Supply Simulation model, a hydraulic model that provided valuable insight into spatial pricing and costing, conservation policies, operating improvements versus increased capital expenditure, user-class subsidization, fire protection capacity, and water quality. Spatial costing incorporated operation and energy costs associated with withdrawal, treatment, and distribution, as well as administrative costs (Clark et al, 1982). Unlike energy use associated with water treatment, the energy required to transport water to a customer is dependent on the head differential between that customer and the water treatment plant. Hydraulic models, such as the Water Supply Simulation model, are powerful and address the problem of equitable pricing based on spatial location and water use characteristics by assigning costs to the water as it flows through elements in the system (Males et al, 1985). For example, water flowing through a pump would be assigned the cost associated with constructing and operating that pump. This methodology provides the added benefit of distribution system energy savings associated with water conservation to be incorporated into optimal water-conservation customer targeting, given that the embedded energy in water is customer-specific and dependent on the energy required to get water to a given customer. Farmani et al (2006) developed an approach to simultaneously optimize for cost, reliability, and water quality in evaluating water supply designs, including optimization of pump scheduling to minimize energy use.

Water–energy relations extend well outside of end uses; however, because end uses account for most (approximately 75%) of the energy use associated with urban water systems, the scope of this work is limited to such end uses (California Energy Commission, 2005). Other studies have addressed additional aspects of energy use associated with urban water systems. Mo et al (2010) used a life-cycle assessment that incorporated not only the direct energy associated with the operation of water supply systems, such as pumps, but also used indirect or embodied energy. These indirect energies include the embodied energy in construction materials and treatment chemicals. Stokes and Horvath (2009, 2006) developed a spreadsheet tool known as the Water-Energy Sustainability Tool to assist planners in decision-making with regard to water supply planning. This tool incorporates life-cycle assessment of materials, energy, and environmental emissions for various treatment alternatives through a cradle-to-grave analysis.

To assess and target the water-saving effects of water conservation practices and associated energy savings, the authors built on previous work (Morales et al, 2013, 2011; Friedman et al, 2011) and developed a methodology that uses parcel-level estimates of water use and optimization methods to determine the cost-effectiveness of water conservation practices based on the amount of water saved. This approach requires an end-use inventory of water-using devices, along with estimates of their water-use efficiency, and frequency of use to carry out a cost-benefit analysis of water conservation practices that is deterministic in nature. For a measure of uncertainty relating to water conservation practices, Groves et al (2007) presented a method of evaluating the uncertainty associated with future water and energy prices critical to evaluating benefits.

> Several models have been proposed to address the variability in indoor water use and demand-management options using probabilistic techniques.

The first section in this article outlines the methodology to estimate the number, efficiency, and water use of fixtures at the parcel level presented by Morales et al (2013). This is followed by an explanation of how to estimate water savings achievable through conservation retrofits and their associated cost. Then a method to estimate the energy savings primarily resulting from the reduced hot-water use attributable to conservation retrofits is discussed. The article concludes with a simple optimization formulation that completely enumerates the net benefits for four BMP options (do nothing, conventional, better, and best) for each end use and for each customer, and ranks the selected options

TABLE 1 Fixture service life, water use efficiency per age group, and frequency-of-use coefficients per 24-h period*

		Current Fixture Efficiencies†			Frequency-of-Use Coefficients‡	
Fixture Type	Service Life—*years*	Pre-1983	1983–1994	Post-1994	Single-Use	Mixed-Use
Residential toilet	40	19	13	6.1	NA	5.10
CII toilet	25	19	13	6.1	1.91	7.65
Urinal	25	9.5	5.7	3.8	5.74	
Residential faucet	15	19	11	8.3	8.10	
CII faucet	15	19	11	5.7	1.89	
Shower	8	25	11	9.5	5.60	
Residential clothes washer	11	210	190	160	0.37	
Prerinse spray valve	5	19	13	6.1	1.44	

CII—commercial, industrial, and institutional; NA—not applicable

*Morales et al, 2013
†Fixture efficiency units are L/flush for toilets and urinals; L/min for faucets, showerheads, and prerinse spray valves; and L/load for clothes washers.
‡Frequency-of-use coefficient units are flushes/person/day for toilets and urinals, minutes/person/day for faucets and showerheads, loads/person/day for clothes washers, and hours/unit/day for prerinse spray valves.

from best to worst. These results provide analysts with not only the optimal overall solution but with direct insight into the blend of fixtures and the target audience for retrofit programs.

WATER END-USE ESTIMATES AT THE PARCEL LEVEL

Morales et al (2013) provided a parcel-level methodology by which to estimate the number of end-use devices, their water-use efficiency, and frequency of use for 64 public-supply land use sectors and seven end-use devices. Fixture counts were estimated using a parcel's heated building area and a series of equations given in Morales et al (2013) for single-use (male-only) toilets, mixed-use toilets, urinals, faucets, showerheads, clothes washers, and prerinse spray valves. Fixture water-use efficiency is a function of a parcel's year built and the fixture's service life. The last change-out year for a given fixture is estimated using Eq 1, and its fixture water-use efficiency is determined through the efficiency-year groups shown in Table 1. This Lagrangian approach to estimating service life is used because it is important to retain the identity of the fixtures over time. Frequency of fixture use is a function of a parcel's population and water use statistics from the literature (Table 1). For residential parcels, the people-per-dwelling unit is taken from the US Census, whereas for commercial, industrial, and institutional (CII) parcels the population is estimated using functional, 24-h equivalent, population coefficients for different land uses based on transportation statistics.

$$\mathrm{LFCY}_{if} = \lfloor (\mathrm{YA} - \mathrm{YB}_i)/\mathrm{SL}_f \rfloor \times \mathrm{SL}_f + \mathrm{YB}_i \qquad (1)$$

The terms used in this equation are defined in the glossary on page E515.

The methodology outlined in this section and described in Morales et al (2013) allows for the estimation of water use per end-use device at the parcel level. With the knowledge of how much water a given device currently uses, it is possible to derive the water saved through retrofitting such a device. The calculation to estimate water use per end-use device is shown in Eqs 2 and 3 for the residential and CII sectors, respectively.

With the knowledge of how much water a given device currently uses, it is possible to derive the water saved through retrofitting such a device.

$$\mathrm{CFWU}_{if} = \mathrm{PPH}_i \times \mathrm{FOU}_f \times \mathrm{FE}_{if}/\mathrm{NF}_{if} \qquad (2)$$

$$\mathrm{CFWU}_{if} = (\mathrm{HA}_i \times \mathrm{FP}_j) \times \mathrm{FOU}_f \times \mathrm{FE}_{if}/\mathrm{NF}_{if} \qquad (3)$$

The terms used in these equations are defined in the glossary on page E515.

WATER END-USE SAVINGS AT THE PARCEL LEVEL

Following Eqs 2 and 3, it is relatively straightforward to calculate the water use for a given retrofit because the only variable in the equation is the water use efficiency of the fixture (Eq 4). The water use efficiencies for several options are presented for residential and CII fixtures in Table 2. Documentation for the data provided in Tables 1 and 2 is shown in Table 3. The water-use savings calculation, as shown in Eq 5, is slightly more complex than the water use calculation because of the need to account for the natural replacement of fixtures. This approach is consistent with the service-life methodology outlined previously, relying on the service life remaining before natural replacement (Eq 6). Thus a fraction of the savings is associated with retrofitting from a current efficiency to the retrofit efficiency level (the service-life-remaining savings period). The remainder of the savings, past the remaining service life, is associated with retrofitting from the current fixture efficiency requirement (likely retrofit type through natural replacement), to the selected retrofit efficiency level.

TABLE 2 Water-use efficiencies and costs of fixture retrofits

		Retrofit Fixture Efficiencies*			Retrofit Fixture Costs—*$*		
Fixture Type	**Service Life—*years***	**Conventional**	**Better**	**Best**	**Conventional**	**Better**	**Best**
Toilet	40†, 25‡	6.1	4.8	4.2	150	180	300
Urinal	25	3.8	1.9	0.0	320	375	275
Residential faucet	15	8.3	5.7	1.9	45	55	70
CII faucet	15	1.9	NA	NA	70	NA	NA
Shower	8	9.5	7.6	5.7	30	31	33
Residential clothes washer	11	160	100	53	450	550	750
Prerinse spray valve	5	6.1	4.7	3.8	50	60	70

CII—commercial, industrial, and institutional, NA—not applicable

*Fixture efficiency units are L/flush for toilets and urinals; L/min for faucets, showerheads, and prerinse spray valves; L/load for clothes washers.
†Residential
‡CII

TABLE 3 BMPs device library, 2012 conditions

Fixture Type	Water Use Efficiency	Category	Hot Water Flow Rate	Fixture Cost *$/unit*	Installation Cost *$/unit*	Maintenance Costs *$/year*	Device Life *years*	Sources
Clothes washer	**L/load**		**L/load**					
	212	Pre-1983	59	NA	NA	45	11	3, 5, 10, 14
	193	1983–1994	54	NA	NA	45	11	3, 5, 10, 14
	155	Post-1994 (conventional)	43	450	100	45	11	3, 5, 10, 14
	102	Better	28	550	100	55	11	3, 5, 10, 12
	53	Best	15	750	100	75	11	3, 5, 10, 12, 13
Faucet	**L/min**		**L/min**					
	19	Pre-1983	14	NA	NA	4	15	4, 8, 10, 14
	11	1983–1994	8	NA	NA	4	15	4, 8, 10, 14
	8	Post-1994 (conventional)	6	45	22	4	15	4, 7, 8, 10
	6	Better	4	55	22	5	15	4, 7, 8, 10
	2	Best	2	70	22	7	15	4, 7, 8, 10
Prerinse spray valve	**L/min**		**L/min**					
	19	Pre-1983	19	NA	NA	5	5	11
	13	1983–1994	13	NA	NA	5	5	11
	6	Post-1994 (conventional)	6	50	10	5	5	11
	5	Better	5	60	10	6	5	11
	4	Best	4	70	10	7	5	11
Showerhead	**L/min**		**L/min**					
	25	Pre-1983	18	NA	NA	3	8	1, 2, 5, 10, 14
	11	1983–1994	8	NA	NA	3	8	1, 2, 5, 10, 14
	9	Post-1994 (conventional)	7	30	13	3	8	1, 2, 5, 7, 10
	8	Better	6	31	13	3	8	1, 2, 5, 7, 10
	6	Best	4	33	13	3	8	1, 2, 5, 10
Toilet	**L/flush**		**L/flush**				**Residential/CII**	
	19	Pre-1983	0	NA	NA	15	40/25	5, 6, 10, 14
	13	1983–1994	0	NA	NA	15	40/25	5, 6, 10, 14
	6	Post-1994 (conventional)	0	150	175	15	40/25	5, 6, 7, 10
	5	Better	0	180	175	18	40/25	5, 6, 10
	4	Best	0	300	175	30	40/25	5, 10
Urinal	**L/flush**		**L/flush**					
	9	Pre-1983	0	NA	NA	25	25	5, 6, 14
	6	1983–1994	0	NA	NA	25	25	5, 6, 14
	4	Post-1994 (conventional)	0	320	100	25	25	5, 6, 7
	2	Better	0	375	100	38	25	5, 6, 7
	0	Best	0	275	100	80	25	5, 6, 9

BMPs—best management practices, CII—commercial, industrial, and institutional; NA—not applicable

[1]A&N, 2005; [2]Allen et al, 2010; [3]*Appliance Magazine*, 2011; [4]Chandler, 2000; [5]Green, 2010; [6]Koeller & Company, 2005; [7]Koeller & Dietemann, 2010; [8]Peterson, 2007; [9]Stumpf, 2007; [10]USEPA, 2005; [11]USEPA, 2011; [12]USEPA & USDOE, 2011; [13]USEPA & USDOE, 2009; [14]Vickers, 2001

$$RFWU_{ifr} = CFWU_{if} \times RFE_{fr}/FE_{if} \quad (4)$$

$$RFWUS_{ifr} = \lfloor (CFWU_{if} - RFWU_{ifr}) \times ASLR_{if}/SL_f \rfloor + \left[\left(CFWU_{if} \times \frac{CFE_f}{FE_{if}} - RFWU_{ifr} \right) \times (SL_f - ASLR_{if})/SL_f \right] \quad (5)$$

$$ASLR_{if} = YA - LFCY_{if} \quad (6)$$

The terms used in these equations are defined in the glossary on page E515.

COST OF WATER CONSERVATION RETROFITS

An estimate of the total present-worth cost of the various water conservation retrofit types is shown in Table 2 for the residential and CII sectors. The basis for these estimates is documented in Table 3. Retrofit costs are highly variable and dependent on the specific conservation evaluation. The cost data in Table 2 are total costs from the customer's perspective. Utilities can use this formulation to estimate the expected decisions by customers regarding fixture replacements with and without utility incentives. Although customers have a direct economic incentive to change fixtures to reduce their water and wastewater utility bill, the utility sees customers' savings as reduced revenue in the short term. Utilities do save operation and maintenance costs in providing less water. Their longer-term savings would be expected to come from reduced capacity expansion costs within the planning horizon.

Given the different service lives of the various water-conserving fixtures, it is important to normalize these costs to a common time scale. This simple conversion is shown in Eq 7, in which fixture retrofit costs are normalized per day of service life.

$$NRFCost_{fr} = RFCost_{fr}/(SL_f \times 365) \quad (7)$$

The terms used in this equation are defined on page E515.

INCORPORATION OF ENERGY END USE

Hot water end-use savings associated with water conservation. Heating water accounts for the bulk (75%) of energy use associated with urban water use (CEC, 2005). Water heating is also the second largest energy end use within the home, behind only space cooling and heating (USDOE, 2009). Modeling of hot water savings associated with water conservation thus offers an additional and significant benefit. The previous section discussed an approach to estimate the water end-use savings associated with conservation. To incorporate hot water into this approach requires knowledge of which end uses employ hot water and what fraction of the water use is hot water. DeOreo and Mayer (2000) give such data as shown in Table 4. Toilets and urinals do not use hot water, whereas prerinse spray valves are assumed to use solely hot water. All other fixtures include hot water for some fraction of their water use. All residential parcels are assumed to use hot water, but only CII parcels with showers or prerinse spray valves are assumed to use hot water. For those parcels with hot water use, the hot-water-use savings associated with water conservation are calculated using Eq 8.

$$RFHotWUC_{ifr} = RFWUS_{ifr} \times PHW_f \quad (8)$$

The terms used in this equation are defined in the glossary on page E515.

Energy savings attributable to hot water end-use savings. The energy use associated with water heating depends on the efficiency of the individual water heater in a home to convert some source of energy, typically electricity or natural gas, to heat hot water. Water heaters vary greatly in type (storage tank versus tankless), source of energy (electricity versus natural gas), and size. The US Energy Information Administration (USEIA, 2009) conducted a residential energy consumption survey that representatively sampled 12,083 households in 2009 to develop statistics on energy use and patterns as well as household demographics. In Florida, as shown in Table 5, the survey found that 96% of water heaters were the storage tank type, with tankless making up only 4% of water heaters. Nearly 89% of water heaters in Florida were also found to operate on electricity, whereas about 9% of water heaters used natural gas. Given the prevalence of electric storage-tank water heaters in Florida, all water heaters are assumed to be electric, with a 90% electric-to-thermal conversion efficiency (USDOE, 2009). A different approach can be taken by assuming a weighted average of energy conversion efficiencies based on the distribution of water heater types using Table 5 in

TABLE 4 Water use measured by hot water per fixture type*

Fixture	Hot Water Use—%
Toilets	0.0
Urinals	0.0
Faucets	72.7
Showerheads	73.1
Clothes washers	27.8
Prerinse spray valves	100.0

*DeOreo & Mayer, 2000

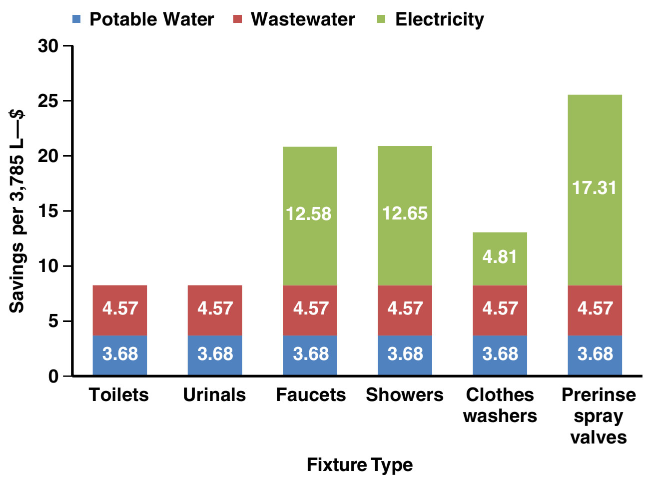
TABLE 5 Distribution of water heaters in Florida by type and fuel use*

	Fuel Use						
Water Heater Type	Electricity	Natural Gas	Propane/LPG	Solar	Other Fuel	Total	%
Storage tank	831	80	14	4	2	931	96.1
Tankless	27	4	7	0	0	38	3.9
Total	858	84	21	4	2	969	100
%	88.5	8.7	2.2	0.4	0.2	100	

LPG—liquid petroleum gas

*USEIA, 2009

FIGURE 1 Cost savings in 2010 for different fixtures based on water saved



Cost data are taken from 2010 national averages of \$0.97/1,000 L for potable water, \$1.21/1,000 L for wastewater (RFC, 2011), and \$0.03/MJ (USEIA, 2011).

which, for example, natural-gas-storage water heaters have an energy conversion efficiency of about 58% (USDOE, 2009).

The electricity use in heating water is derived via the specific heat equation and assuming an inlet and outlet temperature for the water heater (Eq 9). The inlet and outlet temperatures are assumed to be 25 and 55°C, respectively. With a specific heat capacity of 4,186 J/L/°C at 25°C and an energy conversion coefficient of electric-storage-tank water heaters of 0.9, the direct energy intensity of heating water is 113,022 J/L. This direct energy intensity can be applied to the hot water savings associated with conservation retrofits to arrive at electricity savings (Eq 10).

$$DEI = C \times (T_{out} - T_{in})/ECC \tag{9}$$

$$RFHotElecUS_{ifr} = RFHotWUS_{ifr} \times DEI \tag{10}$$

The terms used in these equations are defined in the glossary on page E515.

Eqs 9 and 10 can be used to evaluate the addition of energy savings from reduced hot water use into the water conservation BMP cost-effectiveness calculation. With a savings of 3,785 L, the associated monetary benefits of reduced potable water, wastewater, and energy demand can be computed for each fixture type as shown in Figure 1. The cost data used in this figure are from the 2010 national averages of \$0.97/1,000 L for potable water, \$1.21/1,000 L for wastewater (RFC, 2011), and \$0.03/MJ for energy (USEIA, 2011). As shown in Figure 1, the effect of energy savings is significant and greatly enhances the cost-effectiveness of fixtures that use hot water. The energy savings associated with a retrofit are shown to be about 60% of the total monetary savings for faucets and showerheads, 37% for clothes washers, and 68% for prerinse spray valves.

There are also energy savings beyond the reduction in hot water use associated with clothes-washer retrofits. These retrofit options can offer additional savings in the energy required to run the machine, as well as reduced dryer energy use by further lowering the water content of the clothes within the clothes washer. The clothes washer and dryer energy requirements per load of laundry for the different clothes-washer retrofit options are shown in Table 6. Because these energy requirements are unknown for pre-1983 and 1983–1994 clothes washers, the additional energy savings are associated with the "better" and "best" options, taking the "conventional" option as a baseline. Thus, the additional energy savings of retrofitting to a "better" or 100 L/load clothes washer is 0.223 MJ/load, whereas a "best" or 53 L/load option saves an additional 1.72 MJ/load. These savings are beyond those associated with the hot water saved with clothes washers.

PHYSICAL WATER SAVINGS POTENTIAL

The previous sections detailed the mathematical and data-driven framework for estimating the water and energy use and potential savings associated with various water conservation practices in the residential and CII sectors. The maximum water conservation potential for a specified study year can be found by switching all end uses from their current usage pattern to the best available technology irrespective of cost.

Binary integer programming formulation. A primal/dual relationship exists between the customers (primal) who are assumed to evaluate changing their water-using fixtures to maximize their net benefits and the utility (dual) seeking to minimize revenue

TABLE 6 Clothes-washer and dryer energy use requirements for retrofit options*

Clothes-Washer Retrofit Option	Clothes-Washer Energy—*MJ/load*	Dryer Energy—*MJ/load*	Energy Savings—*MJ/load*
Conventional	0.752	5.15	Baseline
Better	1.094	4.58	0.223
Best	0.410	3.77	1.72

*USDOE, 2000

TABLE 7 Maximum net benefits for a utility* including savings of potable water, wastewater, and energy

Characteristics	W	W+WW	W+E	W+WW+E
Net benefit of water conservation—*\$/d*	20.9	77.1	107.4	179.0
Fixture retrofits	1,504	2,199	2,302	2,315
Water saved—*L/d*	39,512	51,786	58,240	60,034
Energy saved—*MJ/d*	1,662	2,592	3,104	3,134

W—potable water savings, WW—wastewater savings, E—energy savings

*Utility serves 196 homes

losses associated with reduced revenue from its water, wastewater, and energy systems and the cost of incentive programs to reduce demand. This article provides the formulation from the perspective of a utility analyst who is estimating the expected decision of each customer needing to decide whether to retrofit fixtures before the end of their useful service life or to wait until the end of the service life. This section presents a binary integer programming (BIP) formulation by which to determine an optimal combination of water-demand management options, taking into account both water and energy savings based on the parcel-level, bottom-up approach outlined previously.

The objective function for the most general BIP formulation is to maximize total benefits minus total costs. Background information on BIP and duality can be found in Hillier and Lieberman (2010) and Winston (2004). This BIP formulation is shown in Eq 11 wherein the benefits are assumed to be the $/day savings from the value of water and energy saved, the cost being the daily cost of the water fixture in $/day. This can be done by using the value of water savings ($/1,000 L) and energy savings ($/MJ). Good default values are the 2010 national averages of $0.97/1,000 L for potable water, $1.21/1,000 L for wastewater (RFC, 2011), and $0.03/MJ for energy savings (USEIA, 2011). This BIP can be run from the perspective of a customer who is evaluating whether to purchase a new fixture. In this case, the total benefits accrue from saving money by using less water and energy. The customer's cost function can be reduced if the utility provides a financial incentive to select a more efficient fixture—e.g., a 4 L/flush toilet instead of a 6 L/flush toilet.

In this BIP, the numbers of fixtures retrofitted within each parcel serve as the decision variables, and the constraints provide the production function of how fixture retrofits relate to water and energy savings and ensure that the number of fixtures retrofitted of a certain fixture type within a given parcel is less than or equal to the count of that fixture type within that same parcel as determined by the equations presented in Morales et al (2013). The retrofit-fixture energy savings for retrofit option r, fixture type f in parcel i (RFES_{ifr}) in this formulation include the energy savings associated with hot water savings as calculated by Eq 10, but also the additional clothes-washer energy savings associated with clothes washer and dryer energy use as shown in Table 6. The less-than-or-equal inequality allows for the "do nothing" option.

The end-use optimization problem can be big if one simultaneously solves a single BIP for all fixtures. However, only four options exist for each fixture for each customer:

- do nothing if net benefits are negative for all options,
- select the "conventional" option if it maximizes net benefits,
- select the "better" option if it maximizes net benefits, or
- select the "best" option if it maximizes net benefits.

Thus there are four decision variables for each fixture for each customer. Each residential customer has several fixtures, so the total number of decision variables grows rapidly to a number in the hundreds or thousands. Fortunately, this BIP optimization problem can be decomposed into independent decision problems for each fixture because it is simple to enumerate the net benefits for each option and pick the best one.

Simplified ranking alternative. Because the evaluation of water conservation alternatives is a discrete problem, in order to ease the computational requirements of running a parcel-level optimization, the net benefit calculation can be computed for each fixture for each parcel independently. Using this approach for each parcel and fixture type, the option (do nothing, conventional, better, best) with the greatest net benefit is selected. Thus the "optimal" water conservation plan is the sum across all parcels of the parcel-specific options with the greatest net benefit. This alternative is much less computationally tasking than the optimization problem in Eq 11 because each option is simply enumerated once and the greatest net benefit option is selected. In order to compare the BIP and the simplified ranking alternative, both approaches were run for a small utility (196 single-family homes) in central Florida, and their results were found to be identical for the maximization of net benefits shown in Table 7.

The significant effect of the inclusion of wastewater- and energy-saving benefits is also shown in Table 7. By incorporating wastewater and energy savings in the cost-effectiveness evaluation of water conservation practices, more water-use fixtures are cost-effective to retrofit and thus more water can be conserved cost-effectively. The inclusion of wastewater savings in the cost-effectiveness calculation is shown to increase the net benefit of water conservation by 269%, thus increasing the amount of water that is cost-effective to conserve by 31% for the example utility. Similarly, the inclusion of both wastewater and energy savings in the cost-effectiveness calculation increases the net benefit of water conservation by 757%, allowing for 52% more water to be cost-effectively conserved, as compared with the baseline of including only benefits from potable water savings.

$$\mathrm{MaxZ} = \mathrm{ValW} \times w + \mathrm{ValE} \times e - \textstyle\sum_{i,f,r} (x_{ifr} \times a_{if} \times \mathrm{NRFCost}_{fr}) \qquad (11)$$

subject to

$$w = \sum_{i,f,r} (x_{ifr} \times a_{if} \times \mathrm{RFWUS}_{ifr})$$

$$e = \sum_{i,f,r} (x_{ifr} \times a_{if} \times RFES_{ifr})$$

$$x_{ifr} = \{0,1\}$$

$$\sum_{r} x_{ifr} \leq 1$$

The terms used in this equation are defined in the glossary on page E515.

The optimal to-and-from retrofits for the small-utility example are shown in Table 8. With the use of the default data provided in this article, the optimizer shows that it is most cost-effective to retrofit all faucets and showerheads to the most water-efficient or "best" option. For toilets, a mix of BMP options is selected, with 70% of the available toilets being most cost-effective to retrofit to the "better" option and the majority of the remainder

TABLE 8 Optimal to-and-from retrofits for a small utility*

		To				
Toilets—*L/flush*		**6**	**5**	**4**	**Do Nothing**	**Total**
From	19	0	0	0	0	0
	13	0	481	199	0	680
	6	0	0	2	8	10
	Total	0	481	201	8	690
		To				
Faucets—*L/min*		**8**	**6**	**2**	**Do Nothing**	**Total**
From	19	0	0	0	0	0
	11	0	0	0	0	0
	8	0	0	887	0	887
	Total	0	0	887	0	887
		To				
Showerheads—*L/min*		**10**	**8**	**6**	**Do Nothing**	**Total**
From	25	0	0	0	0	0
	11	0	0	0	0	0
	10	0	0	594	5	599
	Total	0	0	594	5	599
		To				
Clothes Washers—*L/load*		**160**	**100**	**53**	**Do Nothing**	**Total**
From	210	0	0	0	0	0
	190	0	0	0	0	0
	160	0	0	152	45	197
	Total	0	0	152	45	197

*Utility serves 196 homes

going to the "best" option. The clothes-washer optimization shows that it is most cost-effective to retrofit 77% of all clothes washers to the "best" option, with "do nothing" for the rest. A utility can provide a further incentive to encourage further fixture retrofits. For example, running the optimizer with a $65 reduced cost for a "best" toilet option results in the "best" option being more cost-effective for the 481 previously selected "better" toilet retrofits. To encourage the retrofitting of all toilets, including the previously selected "do nothings," to the "best" option requires a $90 incentive. Similarly, for it to be cost-effective to retrofit all clothes washers to the "best" option, a $350 incentive is needed.

DISCUSSION AND CONCLUSION

The parcel-level methodology to evaluate water conservation options described in this article allows for a process-level optimization approach that facilitates targeting of customers. Energy costs are seen to have a major effect on the benefits that customers can obtain if they install more efficient retrofits. The financial effects of these changes depend on whether the water utility is also the provider of wastewater and energy services. The inclusion of CII customers in the methodology is significant given the limited understanding of how water is used by such customers.

The focus of this article is on a methodology. This methodology is applicable elsewhere given that similar data sources, such as county property appraiser databases, are available throughout the United States. The default coefficients, coming largely from Florida-specific data, should be updated with data specific to the region being analyzed (Mayer et al, 1999). If no data are available, the default coefficients should provide reasonable estimates for the rest of the country, but the uncertainty of such estimates has not been quantified and is the subject of future work.

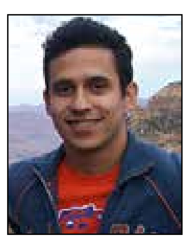
Two approaches are given for evaluating the water conservation of a group of parcels (often those making up a utility): a BIP and a simple-ranking approach. The two approaches are shown to provide identical results for the maximization of net benefits. The simple-ranking approach can be applied directly by enumerating the four options for each fixture type for each customer because each decision is independent of what other customers do. Utility analysts can use this information as an excellent approximation of the expected response of customers to a utility's conservation initiatives.

Future work should include other water end uses such as irrigation by residential customers and cooling towers, laundry, and other process uses by CII customers. The uncertainty associated with the model estimates should also be quantified. Additionally, the BIP formulation could be expanded to include the effect of budget constraints and multi-objective problems.

ACKNOWLEDGMENT

The authors appreciate the support from the Conserve Florida Water Clearinghouse (http://conservefloridawater.org/), which is primarily funded by the Florida Department of Environmental Protection, and the South Florida, St. Johns River, and Southwest Florida Water Management districts. Additional support was provided by the Florida Energy Systems Consortium (www.floridaenergy.ufl.edu/) and a McKnight Doctoral Fellowship award to the senior author.

ABOUT THE AUTHORS



***Miguel A. Morales** is a graduate research assistant in the Department of Environmental Engineering Sciences at the University of Florida, 424 Black Hall, POB 116540, Gainesville, FL 32611; miguel22@ufl.edu. He has been researching urban water use and modeling of conservation for nearly five years. James P. Heaney is a professor in the Department of Environmental Engineering Sciences at the University of Florida. Kenneth R. Friedman is a graduate research assistant in the Department of Environmental Engineering Sciences at the University of Florida. Jacqueline M. Martin is a water resources engineer at E Sciences.*

PEER REVIEW

Date of submission: 02/11/13
Date of acceptance: 05/15/13

Glossary

a_{if} = fixture counts of fixture type *f* in parcel *i* as determined by equations in Morales et al (2013)

$ASLR_{if}$ = average service life remaining before next natural replacement of fixture *f* in parcel *i*

C = specific heat capacity of water (J/L/°C), 4,186 J/L/°C at 25°C

CFE_f = conventional fixture efficiency for fixture *f* (L/flush or L/min)

$CFWU_{if}$ = current fixture water use of fixture type *f* in parcel *i* (L/fixture/day)

DEI = direct energy intensity for heating water (J/L)

e = energy saved (MJ/day)

ECC = energy conversion coefficient of water heater (%)

f = fixture type where *f* ∈ {single-use toilets, mixed-use toilets, urinals, faucets, showerheads, clothes washers, prerinse spray valves}

FE_{if} = fixture efficiency for fixture type *f* in parcel *i* (L/flush or L/min) as determined by Eq 1 and Table 1 (L/flush or min)

FOU_f = frequency of use for fixture *f* as shown in Table 1 (flushes or min/person/day)

FP_j = functional population coefficient for nonresidential FDOR code *j* corresponding to parcel *i* (functional population/m^2)

HA_i = heated building area for parcel *i* (m^2)

i denotes a parcel where *i* ∈ {1, *n*} for a given analysis of *n* parcels

$LFCY_{if}$ = last change-out year of fixture *f* in parcel *i*

NF_{if} = number of fixtures *f* in parcel *i*

$NRFCost_{fr}$ = normalized retrofit fixture cost for retrofit option *r*, fixture type *f* (\$/day)

PHW_f = percent of fixture *f* water use that is hot water as shown in Table 3

PPH_i = people per dwelling unit for parcel *i*

r denotes a retrofit type where r ∈ {conventional, better, best}

$RFCost_{fr}$ = retrofit fixture cost for retrofit option *r*, fixture type *f* (\$)

RFE_{fr} = retrofit fixture efficiency for fixture type *f* and retrofit option *r* as shown in Table 2 (L/flush or L/min)

$RFES_{ifr}$ = retrofit fixture energy savings for retrofit option *r*, fixture type *f* in parcel *i* (MJ/fixture/day)

$RFHotElecUS_{ifr}$ = retrofit fixture energy use savings associated with the heating of less water by retrofit option *r*, fixture type *f* in parcel *i* (J/fixture/day)

$RFHotWUS_{ifr}$ = retrofit fixture hot water use savings for retrofit option *r*, fixture type *f* in parcel *i* (L/fixture/day)

$RFWU_{ifr}$ = retrofit fixture water use for retrofit option *r*, fixture type *f* in parcel *i* (L/fixture/day)

$RFWUS_{ifr}$ = retrofit fixture water use savings for retrofit option *r*, fixture type *f* in parcel *i* (L/fixture/day)

SL_f = service life of fixture type *f* (years)

T_{in} = inlet temperature of water to the hot water heater (°C)

T_{out} = temperature of water at water heater outlet (°C)

ValE = value of the energy saved (\$/MJ)

ValW = value of the water saved (\$/L)

w = water saved (L/day)

x_{ifr} = binary decision variable that determines whether a given retrofit option *r* is selected for fixture type *f* in parcel *i*

YA = year of water conservation analysis

YB_i = effective year built of parcel *i*

Z = objective function (maximize net benefits, \$/d)

REFERENCES

A&N Technical Services, 2005. BMP Costs & Savings Study: A Guide to Data and Methods for Cost-Effectiveness Analysis of Urban Water Conservation Best Management Practices. California Urban Water Conservation Council, Sacramento, Calif.

Allen, L.; Cooley, H.; Heberger, M.; & Gleick, P., 2010. WECalc Data and Assumptions. Pacific Institute, Oakland, Calif.

Appliance Magazine, 2011. U.S. Appliance Industry: Market Value, Life Expectancy and Replacement Picture 2011. June.

Aydinalp, M.; Ugursal, V.I.; & Fung, A.S., 2004. Modeling of the Space and Domestic Hot-water Heating Energy-Consumption in the Residential Sector Using Neural Networks. *Journal of Applied Energy,* 79:2:159. http://dx.doi.org/10.1016/j.apenergy.2003.12.006.

Blokker, E.J.M.; Pieterse-Quirijns, E.J.; Vreeburg, J.H.G.; & van Dijk, J.C., 2011. Simulating Nonresidential Water Demand with a Stochastic End-Use Model. *Journal of Water Resources Planning and Management,* 137:6:511. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000146.

Blokker, E.J.M.; Vreeburg, J.H.G.; & van Dijk, J.C., 2010. Simulating Residential Water Demand with a Stochastic End-Use Model. *Journal of Water Resources Planning and Management,* 136:1:19. http://dx.doi.org/10.1061/(ASCE)WR.1943-5452.0000002.

CEC (California Energy Commission), 2005. Integrated Energy Policy Report. CEC-100-2005-007CMF. Sacramento, Calif.

Chandler, H., 2000 (19th ed.). *Residential Cost Data.* RSMeans, Norwell, Mass.

Clark, R.M.; Fender, V.F.; & Gillean, J.I., 1982. A Spatial Costing System for Drinking Water. *Journal AWWA,* 74:1:18.

Clark, R.M. & Males, R.M., 1986. Developing and Applying the Water-Supply Simulation-Model. Journal AWWA, 78:8:61.

Clark, R.M. & Males, R.M., 1985. Simulating Cost and Quality in Water Distribution. *Journal of Water Resources Planning and Management,* 111:4:454. http://dx.doi.org/10.1061/(ASCE)0733-9496(1985)111:4(454).

DeOreo, W. & Mayer, P., 2000. The End Uses of Hot Water in Single Family Homes from Flow Trace Analysis. www.aquacraft.com/sites/default/files/pub/DeOreo-%282001%29-Disaggregated-Hot-Water-Use-in-Single-Family-Homes-Using-Flow-Trace-Analysis.pdf (accessed May 15, 2012).

Farmani, R.; Walters, G.; & Savic, D., 2006. Evolutionary Multi-objective Optimization of the Design and Operation of Water Distribution Network: Total Cost vs. Reliability vs. Water Quality. *Journal of Hydroinformatics,* 8:3:165.

Friedman, K.; Heaney, J.; Morales, M.; & Palenchar, J., 2011. Water Demand Management Optimization Methodology. *Journal AWWA,* 103:9:74.

Green, D., 2010. *Water Conservation for Small- and Medium-Sized Utilities.* AWWA, Denver.

Groves, D.; Fischbach, J.; & Hickey, S., 2007. Evaluating the Benefits and Costs of Increased Water-Use Efficiency in Commercial Buildings. RAND Corp., Santa Monica, Calif.

Hillier, F. & Lieberman, G., 2010 (9th ed.). *Introduction to Operations Research.* McGraw-Hill, New York.

Jacobs, H. & Haarhoff, J., 2004. Structure and Data Requirements of an End-use Model for Residential Water Demand and Return Flow. *Water SA,* 30:3.

Koeller & Company, 2005. High Efficiency Plumbing Fixtures—Toilets and Urinals. California Urban Water Conservation Council. www.cuwcc.org/docDetail.aspx?id=2880 (accessed Sept. 5, 2007).

Koeller, J. & Dietemann, A., 2010. National Efficiency Standards and Specifications for Residential and Commercial Water-Using Fixtures and Appliances. www.cuwcc.org/WorkArea/showcontent.aspx?id=13966 (accessed Feb. 16, 2011).

Leiby, V. & Burke, M., 2011. Energy Efficiency Best Practices for North American Drinking Water Utilities. Water Research Foundation, Denver.

Maddaus, W. & Maddaus, M., 2004. Evaluating Water Conservation Cost-Effectiveness With an End Use Model. Proc. 2004 AWWA Water Sources Conf., Austin, Texas.

Males, R.M.; Clark, R.M.; Wehrman, P.J.; & Gates, W.E., 1985. Algorithm for Mixing Problems in Water Systems. *Journal of Hydraulic Engineering—ASCE*, 111:2:206. http://dx.doi.org/10.1061/(ASCE)0733-9429(1985)111:2(206).

Mayer, P.; DeOreo, W.; Opitz, E.; Kiefer, J.; Davis, W.; Dziegielewski, B.; & Nelson, J., 1999. *Residential End Uses of Water.* Awwa Research Foundation, Denver.

Mo, W.W.; Nasiri, F.; Eckelman, M.J.; Zhang, Q.; & Zimmerman, J.B., 2010. Measuring the Embodied Energy in Drinking Water Supply Systems: A Case Study in The Great Lakes Region. *Environmental Science & Technology,* 44:24:9516. http://dx.doi.org/10.1021/es1015845.

Morales, M.; Heaney, J.; Friedman, K.; & Martin, J., 2011. Estimating Commercial, Industrial, and Institutional Water Use Based on Heated Building Area. *Journal AWWA,* 103:6:84.

Morales, M.; Martin, J.; Heaney, J.; & Friedman, K., 2013. Parcel-Level Modeling of End-Use Water Demands in Public Supply. *Journal AWWA,* 105:8:E460. http://dx.doi.org/10.5942/jawwa.2013.105.0107.

Peterson, C., 2007. *Popular Mechanics' When Duct Tape Just Isn't Enough: Quick Fixes for Everyday Disasters.* Hearst Books, New York, N.Y.

RFC (Raftelis Financial Consultants), 2011. 2010 Water and Wastewater Rate Survey. AWWA, Denver.

Rosenberg, D., 2007. Probabilistic Estimation of Water Conservation Effectiveness. *Journal of Water Resources Planning and Management,* 133:1:39. http://dx.doi.org/10.1061/(ASCE)0733-9496(2007)133:1(39).

Stokes, J. & Horvath, A., 2006. Life Cycle Energy Assessment of Alternative Water Supply Systems. *International Journal of Life Cycle Assessment,* 11:5:335. http://dx.doi.org/10.1065/lca2005.06.214.

Stokes, J. R., & Horvath, A., 2009. Energy and Air Emission Effects of Water Supply. *Environmental Science & Technology,* 43:8:2680. http://dx.doi.org/10.1021/es801802h.

Stumpf, A., 2007. Waterless Urinals: A Technical Evaluation. US Army Corps of Engineers, Washington.

USDOE (US Department of Energy), 2009. New Technologies, New Savings: Water Heater Market Profile 2009. USDOE, Washington.

USDOE, 2006. Energy Demands on Water Resources: Report to Congress on the Interdependency of Energy and Water. USDOE, Washington.

USDOE, 2000. NOPR Techincal Support Document: Energy Efficiency Standards for Consumer Products: Clothes Washers. USDOE, Washington.

USEIA (US Energy Information Administration), 2011. Sales (Consumption), Revenue, Prices & Customers. www.eia.gov/electricity/data.cfm#sales (accessed Jan. 23, 2013).

USEIA, 2009. Residential Energy Consumption Survey. USEIA, Washington.

USEPA (US Environmental Protection Agency), 2005. Water and Energy Savings from High Efficiency Fixtures and Appliances in Single Family Homes. www.aquacraft.com/sites/default/files/pub/Aquacraft-%282005%29-EPA-Water-and-Energy-Savings-from-High-Efficiency-Fixtures-and-Appliances-in-Single-Family-Homes.pdf (accessed Aug. 10, 2011).

USEPA WaterSense, 2011. Pre-Rinse Spray Valves Field Study Report. USEPA, Washington.

USEPA & USDOE, 2011. Energy Star Qualified Residential Clothes Washers. Energy Star. www.energystar.gov/index.cfm?fuseaction=find_a_product.showProductGroup&pgw_code=CW (accessed Feb. 24, 2011).

USEPA & USDOE, 2009. Clothes Washer Calculator. Energy Star. www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/CalculatorConsumerClothesWasher.xls (accessed Feb. 24, 2011).

Vickers, A., 2001. *Handbook of Water Use and Conservation.* WaterPlow Press, Amherst, Mass.

Widen, J.; Lundh, M.; Vassileva, I.; Dahlquist, E.; Ellegard, K.; & Wackelgard, E., 2009. Constructing Load Profiles for Household Electricity and Hot Water from Time-use Data—Modeling Approach and Validation. *Energy and Buildings*, 41:7:753.

Winston, W., 2004 (4th ed.). *Operations Research—Applications with Algorithms.* Brooks/Cole-Thomson Learning, Belmont, Calif.